IMPROVED SYSTEM AND METHOD FOR HEATING
BIOLOGICAL TISSUE VIA RF ENERGY

5   FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to an improved system and method for heating
biological tissue via RF energy and, more particularly, to a system and method which rely
upon a single electrode. Control of phase and pulse width modulation of applied RF
waves obviate the need for cooling of the skin surface while facilitating efficient heating
10   of underlying layers of tissue such as dermis and subcutaneous layers. Specifically,
heating and contraction of adipose tissues as a means of cellulite reduction is achieved.

Adipose tissues, particularly cellulite, are typically treatable only with a strict
regimen of diet and exercise. Patient compliance with these previously available
regimens is poor. Cellulite occurs when fat cells swell compressing the flow of blood and
15   lymph. This leads to build-up of fluid and toxins. Connective tissue forms hard fibrous
capsules around the fat cells. This results in a "lumpy" appearance. The fat cells involved
are located primarily in the third and most deep (skin) layer, which has a variable by
thickness depending on the amount fat in the subject. Thickness of this layer typically
increases in areas such as abdomen, thighs and buttocks.

20   Previously proposed methods for cellulite treatment include Topical treatment,
Teas and capsules, Cellulite wraps, Endermologie, Mesotherapy, Acthyderm and
Ultrasonic and particularly focused ultrasonic treatment. These techniques have not
demonstrated clinical efficacy in reducing the "lumpy" appearance associated with
cellulite deposits.

25   In addition, thermotherapy using electromagnetic radiation or radio-frequency
(RF) waves has been proposed. RF treatment is more effective than other available
therapy regimens since it permits the body to heal itself. However, previously available
thermotherapy solutions share, as an inherent disadvantage, a tendency to heat the skin to

the point of causing a burn when sufficient RF energy is applied to heat the fat cell target in the deepest skin layer. .

The currently accepted RF technique for heating of biological tissues involves exposing the tissue to RF voltage, which produces RF conductive current through the

5   tissue at a level sufficient to overcome the tissue resistance. The current heats the tissue. This method causes uneven heat accompanied by burning of the outer layer(s) the skin. As a result, systems for implementation of this method share, as an inherent disadvantage, a strict requirement for a cooling mechanism to remove an excessive heat of the skin during the treatment.

10   Previously available alternatives are characterized by disadvantages which are obviated by the present invention.

One example of a prior art system(s) is disclosed in US Patent No. 6,662,054 assigned to Syneron Medical Ltd. This patent teaches deforming the skin so that a region of skin protrudes from the surrounding skin, and applying RF energy to the protruded

15   skin. The system includes one or more RF electrodes, configured to apply conducted RF current to the skin, and a skin deformer, so that a region of skin protrudes out from surrounding skin and is exposed to the conducted RF current, which follows the deforming act. Teachings of this patent have, as an inherent disadvantage, a strict requirement for cooling of the skin to prevent burning.

20   Additional examples of prior art systems which require cooling of the skin to prevent burning include those disclosed in US Patent Application No. 20040002705 assigned to Thermage, Inc. which teaches a method of creating a tissue effect by delivering electromagnetic energy through a skin surface from an electromagnetic energy delivery device coupled to an electromagnetic energy source. At least one of the

25   electromagnetic energy delivery device or electromagnetic energy source includes a memory. A reverse thermal gradient is created through the skin surface to sufficiently heat an underlying tissue site to provide that the temperature of the skin surface is lower than the temperature of the underlying tissue. The reverse thermal gradient is established by use of a cooling system, which is an inherent disadvantage.

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Further additional examples of prior art systems which require cooling of the skin to prevent burning include those disclosed in US Patent Application No. 2004030332 and US Patent No. 5919219 assigned to Thermage, Inc., which teach a system and method for providing treatment to a skin surface by applying RF energy through the skin using a
5 memory for gathering information. These systems include, as an inherent disadvantage, a strict requirement for a cooling lumen for receiving cooling fluid and a number of RF electrodes. The RF electrodes are provided to transfer RF current to the skin and are configured to be capacitive coupled to the skin surface, thus creating a heating effect through RF conducted current.

10 In summary, all previously available methods require the use of a cooling system to cool the outer skin layer throughout the RF treatment. Further, many of the previously available solutions require a memory unit to store local information pertaining to the treated area throughout the treatment. Further, many of the previously available solutions require extensive preliminary adjustments, such as local impedance matching, prior to
15 each treatment. Further, despite use of the phrase "one or more electrodes in many prior art documents, all previously available alternatives share, as an inherent disadvantage, a strict requirement for a return electrode to receive the RF currents after passing tissue being treated. This return electrode for volumetric treatment of adipose tissue (e.g. cellulite) routes a majority of energy through blood and lymphatic vessels. Fat cells are
20 heated only by heat dissipated from these non-target tissues as a result of their inherent resistance.

There is thus a widely recognized need for, and it would be highly advantageous to have, an improved system and method for heating biological tissue via RF energy devoid of the above limitation(s).

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SUMMARY OF THE INVENTION

According to one aspect of the present invention there is provided a system for RF (HF) energy treatment of deep layers of human tissue (e.g. dermis and/or hypodermis) to achieve adipose tissue contraction and/or cellulite reduction.

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The system includes an RF-energy applicator (e.g.spherical shape) which serves as RF-energy coupling antenna that functions in combination with an adjacent tissue as a losses transmission line when contacted with epidermis of the tissue.

5   The system further includes a treated area (part) of human tissue placed in direct contact with RF-energy applicator whereas underlying subcutaneous tissues acts as a dissipative load of the said applicator and the transmission line.

    The system further includes a parallel resonance circuit (RF-resonator) including inductor and capacitor and maximally closely contacted with the said applicator by its central point whereas merit factor of this resonant circuit must be sufficiently high that

10   provides active losses determined by equivalent resistance, which is at least 20 times higher that modulus of impedance of a said area of attached human tissue

    The system further includes impedance matching network (IMN) converting the impedance of treated area of human tissue into 50 Ohms in order to minimize reflected power from human tissue and provide a traveling wave through a human tissue.

15   The system further includes a phase shifting device at the input of the IMN providing an achievement of maximum of RF traveling -wave at a predetermined depth under the surface or on the surface.

    According to another aspect of the present invention there is provided a method, which includes operation of the system.

20   According to further features in preferred embodiments of the invention described below the applicator is made from Al, Ag, Au, copper, or copper and aluminum alloys and coated with dielectric material.

    According to still further features in the described preferred embodiments the applicator is made from Al coated by alumina.

25   According to still further features in the described preferred embodiments the applicator is moved on the surface of treated skin.

    According to still further features in the described preferred embodiments the feeding cable connects RF- applicator and RF-resonator with impedance matching systems.

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According to still further features in the described preferred embodiments the feeding cable has resonance (n*λ/2) length, where λ- is a wavelength of RF-energy in the cable material and n – is whole number

According to still further features in the described preferred embodiments the impedance matching system provides compensation of the reactance of the attached piece of human tissue.

According to still further features in the described preferred embodiments the impedance matching system is fixed L, T or Π- shape structure.

According to still further features in the described preferred embodiments the impedance matching system is broadband impedance transformer.

According to still further features in the described preferred embodiments the impedance matching system is variable.

According to still further features in the described preferred embodiments the phase shifter is trombone type.

According to still further features in the described preferred embodiments the phase shifter is constructed of coaxial cable.

According to still further features in the described preferred embodiments the phase shift provided by the phase shifter is variable in time.

According to still further features in the described preferred embodiments the impedance meter (sensor) is inserted between matching system and RF-applicator.

According to still further features in the described preferred embodiments the said impedance matching system is controllable by feedback system obtaining the signal from the said impedance meter (sensor) for the purpose of reaching the optimal impedance matching and maximal energy deposition into human tissue.

According to still further features in the described preferred embodiments the coupled energy is delivered from RF-generator (amplifier).

According to still further features in the described preferred embodiments the delivered RF-power is coupled in continuous or pulsing mode.

According to still further features in the described preferred embodiments the control of the energy coupled to human tissue is achieved by variation of amplitude or duty cycle of RF-power in pulsing mode (PWM- control).

According to still further features in the described preferred embodiments the certain part of human body is in contact with second point of the said RF-resonator (for example ground).

According to still further features in the described preferred embodiments the operation is provided on the resonance frequency of human body.

According to still further features in the described preferred embodiments the treatment with RF-applicator t is combined with the laser treatment.

According to still further features in the described preferred embodiments the treatment with RF-applicator t is combined with ultrasonic treatment

According to still further features in the described preferred embodiments the treatment with RF-applicator t is combined with UV-treatment

According to still further features in the described preferred embodiments the treatment with RF-applicator t is combined with plasma treatment

According to still further features in the described preferred embodiments the treatment with RF-applicator t is combined with flash-lamp treatment.

According to one aspect of the present invention there is provided an improved system for thermal treatment of a selected target within a subject, the system includes: (a) an RF energy source capable of producing an output RF power signal directed to an applicator contactable with a surface of a biological tissue belonging to the subject, the applicator capable of delivering a desired amount of energy to a predetermined energy dissipation zone beneath the surface of the biological tissue, the selected target positioned within the predetermined energy dissipation zone; (b) a phase shifter, the phase shifter capable of shifting a phase of directed traveling waves of the output signal so that energy therefrom is concentrated primarily in the predetermined energy dissipation zone, which lies at a desired depth beneath the surface of the biological tissue; (c) an impedance matching network (IMN), the IMN capable of converting the impedance of the biological

tissue belonging to the subject from a nominal value to a corrected value, *the corrected value* matching an impedance characteristic of the RF transmission line so that the directed traveling wave may pass through the surface of the biological tissue without being converted to a standing wave; (d) an RF resonator located in the applicator, the RF

5   resonator capable of cyclically accumulating and releasing the desired amount of energy, the RF resonator further capable of concentrating the desired amount of energy so that a significant portion thereof is concentrated in the predetermined energy dissipation zone; and (e) the applicator capable of conveying the output RF power signal from the RF energy source through the surface of the biological tissue to the predetermined energy

10   dissipation zone after the output has been processed by the phase shifter, the IMN and the resonator. Operation of the system produces a reverse thermal gradient so that the surface of the biological tissue is maintained at a lower temperature than the predetermined energy. The absence of a ground electrode permits free propagation of the waves of the output RF power signal in the energy dissipation zone.

15   According to another aspect of the present invention there is provided an improved method for thermal treatment of a selected target within a subject. The method includes: (a) providing an output RF power signal directed to an applicator contactable with a surface of a biological tissue belonging to the subject, (b) employing a phase shifter to shift a phase of directed traveling waves of the output RF power so that energy therefrom

20   is concentrated primarily in a predetermined energy dissipation zone which lies at a desired depth beneath the surface of the biological tissue, wherein the selected target is positioned within the predetermined energy dissipation zone; (c) converting the impedance of the biological tissue belonging to the subject from a nominal value to a corrected value, the corrected value matching an impedance characteristic of RF-

25   transmission line so that the directed traveling wave may pass through the surface of the biological tissue without being converted to a standing wave by means of an impedance matching network (IMN); (d) cyclically accumulating in an RF resonator located in the applicator, and releasing therefrom, the desired amount of energy, (e) concentrating the desired amount of energy in the RF resonator so that a significant portion thereof is

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concentrated in the predetermined energy dissipation zone upon release therefrom; and

(f) conveying the output signal of RF energy through the surface of the biological tissue to the predetermined energy dissipation zone after the output has been processed by the phase shifter, the IMN and the resonator by means of the applicator. Performance of (a) –(f) produces a reverse thermal gradient so that the surface of the biological tissue is maintained at a lower temperature than the predetermined energy dissipation zone, thereby obviating the need for a cooling device. The absence of a ground electrode permits free propagation of the waves in the output signal in the energy dissipation zone.

According to yet another aspect of the present invention there is provided an improved method for cellulite treatment. The method includes: (a) providing an output signal of RF energy directable to an applicator contactable with a surface of a biological tissue belonging to the subject, (b) employing a phase shifter to shift a phase of directed traveling waves of the output RF power so that energy therefrom is concentrated primarily in a predetermined energy dissipation zone which lies at a desired depth beneath the surface of the biological tissue, wherein the selected target is positioned within the predetermined energy dissipation zone, the predetermined energy dissipation zone including at least one cellulite body; (c) converting the impedance of the biological tissue belonging to the subject from a nominal value to a corrected value, the corrected value matching an impedance characteristic of RF-transmission line so that the directed traveling wave so that the output signal may pass through the surface of the biological tissue without being converted to a standing wave by means of an impedance matching network (IMN); (d) cyclically accumulating in an RF resonator located in the applicator, and releasing therefrom, the desired amount of energy, (e) concentrating the desired amount of energy in the RF resonator so that a significant portion thereof is concentrated in the predetermined energy dissipation zone upon release therefrom; and(f) conveying the output power from the RF energy source through the surface of the biological tissue to the predetermined energy dissipation zone after the output has been processed by the phase shifter, the IMN and the resonator by means of the applicator. Performance of (a) –(f) produces a reverse thermal gradient so that the surface of the biological tissue is

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maintained at a lower temperature than the predetermined energy dissipation zone, thereby obviating the need for a cooling device. The absence of a ground electrode permits free propagation of the waves in the output signal in the energy dissipation zone. The at least one cellulite body is heated to a greater degree than a tissue adjacent thereto.

According to further features in preferred embodiments of the invention described below, the system further includes a pulse width modulation (PWM)- controller, the PWM- controller capable of causing the RF energy source to deliver the output signal in pulses of a desired amplitude, a predetermined duration with a desired repetition frequency for average output power control.

According to still further features in the described preferred embodiments the system further includes a dielectric barrier positionable between the applicator and the surface of the biological tissue; the dielectric barrier preventing transmission of a conductive current.

According to still further features in the described preferred embodiments the applicator is made from at least one metal selected from the group consisting of aluminum, silver, gold, copper and alloys thereof.

According to still further features in the described preferred embodiments the dielectric barrier is supplied as a dielectric coating on the applicator.

According to still further features in the described preferred embodiments the applicator is constructed primarily of aluminum and the dielectric barrier is supplied as an alumina coating.

According to still further features in the described preferred embodiments the applicator is movable on the surface of the biological tissue as a means of altering a location of the energy dissipation zone.

According to still further features in the described preferred embodiments the system further includes a feeding cable, the feeding cable connecting the RF- applicator and the RF-resonator with the IMN.

According to still further features in the described preferred embodiments the feeding cable has a resonance length defined by n*λ/2 length, where λ is a wavelength of RF-energy in the cable material and n is a whole number.

According to still further features in the described preferred embodiments the IMN includes a fixed structure characterized by a shape selected from the group consisting of L shaped, T shaped and Π-shaped structure.

According to still further features in the described preferred embodiments the IMN includes a broadband impedance transformer.

According to still further features in the described preferred embodiments the IMN is variable.

According to still further features in the described preferred embodiments the phase shifter includes a trombone type phase shifting mechanism. Trombone type phase shifters are well known to those of ordinary skill in the art and are described in detail at www.microwaves101.com/encyclopedia/phaseshifters.cfm which is fully incorporated herein by reference (see Appendix A).

According to still further features in the described preferred embodiments the phase shifter is at least partially constructed of coaxial cable.

According to still further features in the described preferred embodiments a phase shift provided by the phase shifter is variable.

According to still further features in the described preferred embodiments the energy delivered to the predetermined energy dissipation zone is coupled in continuous or pulsing mode. The RF-energy is produced in the form of sinusoidal signal that can be modulated by rectangular pulses with lower frequency by PWM controller)

According to still further features in the described preferred embodiments the RF-energy is characterized by a resonance frequency which matches a known natural resonance frequency of the selected target.

According to still further features in the described preferred embodiments the system further includes at least one additional component selected from the group

consisting of a laser beam, an ultrasonic transducer, a UV light source, a plasma treatment device and a flash lamp.

According to still further features in the described preferred embodiments the providing indicates provision of the output signal in pulses of a predetermined duration with a desired frequency.

According to still further features in the described preferred embodiments the method further includes interposing a dielectric barrier between the applicator and the surface of the biological tissue. The dielectric barrier prevents transmission of a conductive current.

According to still further features in the described preferred embodiments the method further includes constructing the applicator primarily of aluminum. More preferably, the dielectric barrier is supplied as an alumina coating on an aluminum applicator.

According to still further features in the described preferred embodiments the method further includes moving the applicator with respect to the surface of the biological tissue as a means of altering a location of the energy dissipation zone.

According to still further features in the described preferred embodiments the method further includes employing a feeding cable to connect the RF- applicator and the RF-resonator with the IMN.

According to still further features in the described preferred embodiments the method further includes varying the phase shift provided by the phase shifter.

The present invention successfully addresses the shortcomings of the presently known configurations by providing an improved system and method for heating biological tissue via RF energy, which relies upon a single electrode and does not require a cooling system to prevent burning of skin.

Implementation of the method and system of the present invention involves performing or completing selected tasks or steps manually, automatically, or a combination thereof. Moreover, according to actual instrumentation and equipment of preferred embodiments of the method and system of the present invention, selected steps

could be implemented by hardware or by software on any operating system of any firmware or a combination thereof. For example, as hardware, selected steps of the invention could be implemented as a chip or a circuit. As software, selected steps of the invention could be implemented as a plurality of software instructions being executed by

5   a computer using any suitable operating system. In any case, selected steps of the method and system of the invention could be described as being performed by a data processor, such as a computing platform for executing a plurality of instructions.

BRIEF DESCRIPTION OF THE DRAWINGS

10   The invention is herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood

15   description of the principles and conceptual aspects of the invention. In this regard, no attempt is made to show structural details of the invention in more detail than is necessary for a fundamental understanding of the invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice.

20   In the drawings:

FIG. 1 is a simplified schematic diagram illustrating RF-power coupling to a treated tissue according to the present invention.

FIG. 2 is simplified schematic diagram of RF-system according to the present invention illustrating the principles of output power control with PWM and treating space

25   control with phase shifting of incident RF-wave in accordance with a preferred embodiment of the present invention

FIG. 3 illustrates an impedance matching system in accordance with the present invention.

FIG. 4 is a thermo-gram illustrating heat distribution resulting from operation of a system according to the present invention using a slice of an apple as a target.

FIG. 5 is a thermo-gram illustrating heat distribution resulting from operation of a prior art system according to the present invention using a slice of an apple as a target.

FIG. 6 is a simplified flow diagram illustrating a sequence of events associated with performance of a method according to the present invention.

BRIEF DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention is of an improved system and method for heating biological tissue via RF energy, which requires only a single electrode.
Specifically, control of phase and pulse with modulation (PWM)-control of applied RF waves through the single electrode of the present invention obviate the need for cooling of the skin surface while facilitating efficient heating of underlying layers of tissue such as dermis and subcutaneous layers. As a result, the desired heating and contraction of adipose tissues is achieved. This allows, for the first time, non-invasive cellulite reduction.

The principles and operation of an improved system and method for heating biological tissue via RF energy according to the present invention may be better understood with reference to the drawings and accompanying descriptions.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments or of being practiced or carried out in various ways. In addition, it is to be understood that the phraseology and terminology employed herein is for the purpose of description and should not be regarded as limiting.

The present invention offers several advantages with regard to previously available alternatives.

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A single electrode, or applicator, employed without a ground electrode permits homogeneous application of RF-energy, which is directed primarily towards rotation, and vibration of dipole molecules, especially water molecules, in the applied electromagnetic wave.

Phase shifting techniques provide the possibility of concentration of RF-energy at a predetermined depth with respect to the skin surface by variation of position of RF-wave maximum

Organization of energy dissipation inside of subcutaneous tissue insures maintenance of a relatively low temperature on the skin surface (epidermis). This provides a reverse thermal gradient without use of an external cooling system.

Preferably, an Alumina- ceramic-coated applicator minimizes energy losses and prevents unwanted conductive current through human tissue

A supporting parallel resonator attached in proximity to the applicator accumulates RF-energy and provides efficient excitation of the applicator and high RF-voltage on the application surface.

Application of high RF-power in short-pulses provides fast and effective heating of cellulite capsules with relatively low average RF-power level.

PWM-control of output RF-power and simple IMN techniques provide good matching and low RF-power reflection with all types of human tissues. The additional advantage of applied fixed IMN and PWM-control ensure good impedance matching with variable types of human tissue without complicated impedance matching correction. The RF-applicator can be moved on the treated surface.

It will be appreciated that volumetric fatty tissue treatment requires deployment of a homogeneous RF-wave (through cross-section transversal to wave propagation) with maximum at a desired distance from the electrode-applicator. This homogeneous and high intensity RF-wave insures efficient heating of cellulite capsules and fat cells because they retain water molecules. In contrast, blood and lymphatic vessels will not be subject to undesired heating because the natural circulation of water molecules in these vessels

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provides convective cooling. Further, blood and lymphatic vessels provide conductive

cooling for other non-target tissues such as muscle, nerve tissue and connective tissue.

Referring now to the figures, principle components of a system according to the

present invention and their operation are explained in greater detail.

5   The present invention is primarily embodied by a system 30 (Figures 1-3) for

thermal treatment of a selected target within a subject. System 30 includes an RF energy

source 10 capable of producing an output RF power signal 17 directed to an applicator 3

contactable with a surface 6 of a biological tissue 4 belonging to the subject. Applicator 3

is capable of delivering a desired amount of energy to a predetermined energy dissipation

10   zone 5 beneath surface 6 of biological tissue 4. The selected target is positioned within

the predetermined energy dissipation zone 5 and is represented in the figures as water

molecules 1.

System 30 further includes a phase shifter (e.g. trombone-type phase shifter 14).

Phase shifter 14 is capable of shifting a phase of directed traveling waves of output

15   power17 so that energy therefrom is concentrated primarily in the predetermined energy

dissipation zone 5, which lies at a desired depth beneath surface 6 of biological tissue 4.

System 30 further includes an impedance matching network 11 (IMN capable of

converting the impedance of biological tissue 4 belonging to the subject from a nominal

value (e.g. 250-350 Ohms) to a corrected value (e.g. 50 Ohms). The corrected value

20   matches an impedance characteristic of RF energy source and RF transmission line

including phase shifter 14 and cable 11, so that output RF traveling wave 17 may pass

through surface 6 of biological tissue 4 without being converted to a standing wave.

System 30 further includes an RF resonator 13 located in applicator 3. , RF

resonator 13 is capable of cyclically accumulating and releasing the desired amount of

25   energy and is further capable of concentrating the desired amount of energy so that a

significant portion thereof may be transmitted to predetermined energy dissipation zone

5.

System 30 further includes applicator 3 capable of conveying output RF power signal 17

from the RF energy source 10 through surface 6 of biological tissue 4 to predetermined energy

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dissipation zone **5** after output **17** has been processed by the phase shifter **14**, IMN **11** and resonator **13**.

Typically, operation of system **30** results in 2 to 4% loss of energy from output signal **17** with ban additional 2-4% reflection of energy from output signal **17**. This means that system 30 can reliably deliver 90-95% of energy from output signal **17** into zone **5**. Neither concentration of energy from output signal **17** into a small zone **5**, nor this degree of efficiency, were achievable with previously available alternatives. IMN **11** reduces reflection of applied output signal **17** from surface **6** thereby increasing efficiency of delivery of energy to energy dissipation zone **5**.

It is an inherent advantage of system **30** that its operation produces a reverse thermal gradient so that surface **6** of biological tissue **4** is maintained at a lower temperature than predetermined energy dissipation zone **5** without use of a cooling device.

Further, the absence of a ground electrode from system **30** permits free propagation of the waves of output RF power signal **17** in energy dissipation zone **5**.

These factors serve to greatly increase the degree of heating of water molecules **1** relative to the degree of heating of water molecules **1** achieved with prior art alternatives.

The inherent advantages of system **30** are clear from comparison of thermo-grams of energy dissipation zone **5** using system **30** (Figure 4) and a prior art bipolar (i.e. 2 electrode) system (Figure 5). Each thermo-gram is accompanied by a key on the left which indicates that the colors white, yellow, orange, red, green, blue and violet represent concentrations of heat energy in decreasing order. In each figure, an apple slice is used as biological tissue **4**. Specifically, it is clear that system **30** moves zone **4** away from surface **6** of tissue **4**.

Figure 4 clearly shows that when applicator **3** of system **30** is contacted with surface **6** of tissue **4**, delivery of output energy **17** results in delivery of energy primarily to zone **5**. Line **26** passes through the center of zone **5**. The temperature at surface **6** of tissue **4** is clearly lower than along line **26** in zone **5**. In other words, operation of system

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30 creates a reverse thermal gradient and obviates the need for a cooling system to prevent undesired overheating of surface 6.

In sharp contrast, Figure 5 clearly shows that when applicator 3 of a prior art bipolar system is contacted with surface 6 of tissue 4, delivery of output energy 17 results in delivery of energy primarily to a zone 5 which is adjacent to surface 6 of tissue 4. This reduces the distance between line 26, which passes through the center of zone 5, and surface 6. In other words, the prior art bipolar system delivers heat energy primarily in proximity to surface 6. The thermo-gram of Figure 5 illustrates a distribution of heat energy observed when the prior art bipolar system is operated with a cooling system. Despite this cooling system, no reverse thermal gradient is achieved.

Optionally, but preferably, system 30 further includes a PWM controller, the PWM controller 12 capable of causing the RF energy source to deliver the output power signal in pulses of a predetermined duration and amplitude with a desired frequency. For example, the operating RF-frequency is 40.68 MHz, a PWM-frequency is 1 to 20 kHz and a duty cycle is 10 to 90 %.

According to some preferred embodiments of the invention, applicator 3 is made from metals such as, for example, aluminum, silver, gold, copper or alloys thereof. Alternately, or additionally, a dielectric barrier 2 may be positioned between applicator 3 and surface 6 of biological tissue 4. Dielectric barrier 2 prevents unwanted transmission of a conductive current to tissue 4. According to some preferred embodiments of the invention, dielectric barrier 2 is supplied as a dielectric coating on applicator 3. According to a most preferred embodiment, applicator 3 is constructed primarily of aluminum and dielectric barrier 2 is supplied as an alumina coating.

Optionally, but preferably, applicator 3 is movable on surface 6 of biological tissue 4 as a means of altering a location of energy dissipation zone 5.

Optionally, but preferably, system 30 further includes a feeding cable 7, the feeding cable 7 connecting RF- applicator 3 and the RF-resonator 13 with IMN 11. Optionally, but preferably, feeding cable 7 has a resonance length defined by $n*\lambda/2$

length, where λ is a wavelength of RF-energy in the cable material and n is a whole number.

Optionally, but preferably, IMN **11** includes a fixed structure characterized by a shape such as, for example, L shaped, T shaped or *Π*-shaped structure. Optionally, but preferably, IMN **11** includes a broadband impedance transformer. Optionally, but preferably, IMN **11** is variable.

Optionally, but preferably, phase shifter **14** includes a trombone type phase shifting mechanism.

Alternately, or additionally, phase shifter **14** may be at least partially constructed of coaxial cable.

Optionally, but preferably, phase shifter **14** provides a variable phase shift. .

Optionally, but preferably, RF-generator **10** delivers coupled energy.

Optionally, but preferably, the energy delivered to the predetermined energy dissipation zone **5** is coupled in a continuous or a pulsing mode. RF-generator **10** produces output **17** in the form of a sinusoidal signal which may be modulated by rectangular pulses with lower frequency. This may be accomplished, for example, by PWM controller **12**.

According to one most preferred embodiment of the invention, system **30** employs RF-energy **17** which is characterized by a resonance frequency that matches a known natural resonance frequency of the selected target.

Optionally, but preferably, system **30** may further include additional components, such as, for example, a laser beam, an ultrasonic transducer, a UV light source, a plasma treatment device and a flash lamp.

The present invention is further embodied by an improved method **100** for thermal treatment of a selected target within a subject. Method **100** includes:
providing **102** output RF power signal **17** directed to applicator **3** contactable with surface **6** of biological tissue **4** belonging to the subject.

Method **100** includes employing **104** a phase shifter **14** to shift a phase of RF-traveling waves of output RF power **17** so that energy therefrom is concentrated primarily

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in predetermined energy dissipation zone **5** which lies at a desired depth beneath surface **6** of biological tissue **4**. The selected target is positioned within energy dissipation zone **5**.

Method **100** further includes converting **106** impedance of biological tissue **4** belonging to the subject from a nominal value to a corrected value. The corrected value matches a characteristic impedance characteristic of RF energy source and RF transmission line including a cable **11** and a phase shifter **14** so that output RF-traveling wave **17** may pass through surface **6** of biological tissue **4** without being converted to a standing wave by means of IMN **11**;

Method **100** further includes cyclically **108** accumulating/releasing in an RF resonator **13** located in applicator **3** the desired amount of energy.

Method **100** further includes concentrating **110** the desired amount of energy in RF resonator **13** so that a significant portion thereof is concentrated in the predetermined energy dissipation zone **5** upon release from resonator **13**.

Method **100** further includes conveying **112** output **17** from RF energy source **10** through surface **6** of biological tissue **4** to predetermined energy dissipation zone **5** after output **17** has been processed by the phase shifter **14**, the IMN **11** and resonator **13** by means of applicator **3**.

Performance of **102**, **104**, **105**, **108**, **110** and **112** produce **114** a reverse thermal gradient so that surface **6** of biological tissue **4** is maintained at a lower temperature than predetermined energy dissipation zone **5**, thereby obviating the need for a cooling device.

The absence of a ground electrode permits free propagation of the waves in output signal **17** in energy dissipation zone **5**.

According to still further features in the described preferred embodiments the providing indicates provision **118** of output signal **17** in pulses of a predetermined duration and an amplitude with a desired frequency as detailed hereinabove.

Preferably, method **100** further includes interposing **120** a dielectric barrier **2** between applicator **3** and surface **6** of biological tissue **4**. Dielectric barrier **2** prevents transmission of a conductive current. Preferably, method **100** further includes

constructing applicator **3** primarily of aluminum. More preferably, dielectric barrier **2** is supplied as an alumina coating on an aluminum applicator **3**.

Preferably, method **100** further includes moving **122** applicator **3** with respect to surface **6** of biological tissue **4** as a means of altering a location of energy dissipation zone **5**.

Optionally, but preferably, method **100** further includes employing **124** a feeding cable **XX** to connect applicator **3**, and resonator **11** with IMN **11**.

Optionally, but preferably, method **100** further includes varying **126** the phase shift provided by phase shifter14.

Method **100** is optimally employed for cellulite treatment by selecting a predetermined energy dissipation including at least one cellulite body which serves as a target which is heated to a greater degree than tissue adjacent thereto. As a result, cellulite is reduced **128**.

The present invention relies upon RF-heating of biological tissues via rotation of molecules of the water molecules **1** (fig.1), which are dipole structures, in an alternating electromagnetic field. In order to avoid a conductive HF-current a dielectric barrier **2** provides insulation between the applicator **3** and a biological tissue surface **6**.

Preferably, applicator **3** is constructed from aluminum or an aluminum alloy covered by alumina coating with a thickness 40-50 μm. Applicator **3** serves also to cool tissue surface **6**, thereby obviating the need for a separate cooling system.

Applicator **3** can be also described as an antenna coupler that irradiates the RF-wave into deep tissue **4**. The resultant dissipation of the energy load can be described as irradiative coupling of RF-energy.

The area through which applied RF energy is primarily applied **5** is determined by the contact area between tissue surface **6** and applicator **3** and by the phase of incident electromagnetic wave pulses **17**. The energy diverges from surface **6** and is effectively dissipated **5** through tissue **4**. The depth of RF-energy penetration depends on RF-power and area of applicator and phase shift of electromagnetic wave. By application of phase

20

shifting device 14 it is possible to adjust a position of energy dissipation zone 5 and to coincide with a selected target (e.g. cellulite lesions).

The applied oscillating RF-field stimulates all dipole molecules (mostly water molecules 1) to rotate and vibrate with consequent heating of energy dissipation zone 5. Zone 5 may be controlled by phase shifting device 14 between RF-generator 10 and applicator 3. Heating will be primarily in adipose tissue because it is rich in liquids but not subject to convective cooling as blood vessels are. Thus, collagen capsules will be destroyed by heating because their high thermo isolation. The pulse width modulation (PWM) control 12 of output RF- power that provide a possibility to keep a high peak RF-power with low average power level will leads to the most efficient collagen capsule destruction.

It is an advantage of the present invention that epidermal layer 6 is heated much less than subcutaneous tissue 4. An inverse thermal gradient that is provided by intensive cooling of epidermis that described by Thermage patents is achieved automatically with deep heating of tissues.

The absence of a second or ground electrode in the pictured configuration permits free propagation of RF waves inside tissue 4.

In order to maximize transmission of RF-energy from RF-source 10 (Figure 2) through resonant cable 7 to applicator 3, it is connected to the central point of a parallel resonator 13 including a capacitor 8 and an inductor 9 connected in parallel and characterized by very high-Q- factor for example more than 20.

The delivered oscillating RF-power (e.g. 25-300 watts) is stored in the resonator 13 therefore an active (dissipative) load of resonator 13 is only an adjacent tissue.

The active losses of resonator 13 are very low (20-50 times less than energy dissipated inside tissue 4). The intermittent discharge of capacitor 18 and the inductor 19 is coupled through applicator 3 to tissue 4.

RF-generator 10 capable of producing 200-400 Watts full power at 40.68 MHz operating frequency demonstrates an optimal performance at 50 Ohms resistive load. Optimal performance means minimal reflected RF-power with maximum RF-forward

power dissipated by a load. Thus, the real load that includes treated volume **5** of tissue **4** is matched as 50 Ohms load.

The used impedance matching network (IMN **11**; see Fig.2) is fixed (the elements are not variable operatively); therefore operation occurs without RF-power amplitude changes. The control of output power is reached by PWM-control (pulse width modulation). PMW achieves modulation of output power by rectangular power pulses applied with a frequency lower than that of the RF wave. In order to decrease RF-power coupling it is necessary to reduce a duty cycle of PWM. PWM-controller **12** produces rectangular pulses with a modulation frequency range of 2-10 kHz. The duty cycle may be varied from 5 to 100%. The shape of RF-power pulse **17** is showed in Fig.2. The PWM-control of output RF-power permits high peak RF-power level in heating zone **5** with lower average power. This provides efficient heating of adipose capsules with minimal impact on blood vessels and other tissues.

The reflected RF-power is 1-2 % of output power therefore 98% of output power is dissipated in the treated volume. Typically, we concentrate energy in adipose tissue therefore coupled RF-energy is dissipated by fat cells, cellulite capsules and by blood and lymphatic liquids. The energy that produces a useful job in fat cells and cellulite tissue will reach 70-80 % of total energy coupled to the volume. The rest energy is dissipated through diffusion of the heat to the surface and by convection of natural liquids of human body.

Applicator **3** is connected to parallel resonator **13**. Applicator **3** and resonator **13** are physically positioned inside of operating hand-piece **22** used for treatment procedure. The IMN-system locates inside the main system **23**. In order to avoid a mismatching phase shift between the applicator **3** and the IMN **11**, the length of cable **7** is equal to the whole number *(n)* of wavelength of RF-energy *(λ)* in the cable material.

In order to reach necessary amplitude under the surface **6** of tissue **4**, a phase shifting system (e.g. trombone-type system **14**) is inserted between output of RF-generator **10** and an input of IMN **11**. The position of the maximum of energy dissipation can be controlled by this phase shifting system and can be placed under

surface **6** of tissue **4**. In order to control the depth of RF-energy penetration the length of trombone can be shortened that change a position of dissipated electromagnetic wave in the tissue or an area of the maximum of RF-voltage. Consequently, RF-energy will be dissipated most efficiently in the volume around maximum of the RF-voltage.

5   The phase shifter **14** can be controlled automatically, for example by motors **15**. This change of phase could be linear or periodical that provides a displacement of maximal heating zone inside the tissue or scanning of maximal heating zone position.

      The practical implementation of impedance matching system **11** is illustrated by Fig.3. The RF-power delivered from RF-generator **10** through coaxial cable **16** is

10   modulated by rectangular pulses **17**. Because RF-generator **10** is matched to 50 Ohms and impedance of human tissue is close to 300 Ohms, it is necessary to convert 50 to 300 Ohms with compensation of electromagnetic reactance of tissue **4**. This is achieved with impedance matching network **11**. L-type simple fixed IMN consisting of RF-capacitor **18** and RF-inductor **19** (Fig.3) were applied for this purpose. Half-wave cable **7** is applied

15   for transmission of RF-energy from IMN **11** to RF applicator **3** without phase shifting that is controllable by phase shifting system. The measured impedance in the point **20** is 50 Ohms and in the point **21** is 300 Ohms. Impedance matching networks of various types may be employed without significantly altering performance of the present invention. Regardless of the exact IMN type employed, the IMN **11** can be variably

20   and/or automatically controlled to trace an impedance changing.

      It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention, which are, for brevity, described in the context of a single embodiment, may also be provided separately

25   or in any suitable subcombination.

      Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the

appended claims. All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In

5 addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention.
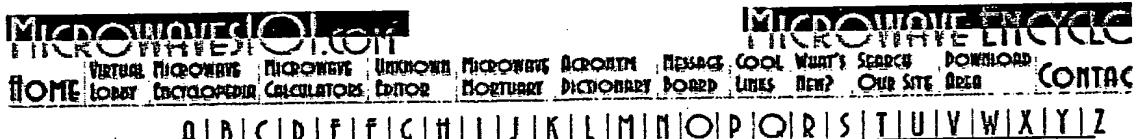
Phase shifters

Upated September 13, 2004

Phase shifters are used to change the transmission phase angle (phase of S21) of a network. Ideally phase shifters provide low insertion loss, and approximately equal loss in all phase states. While the loss of a phase shifter is often overcome using an amplifier stage, the less loss, the less power that is needed to overcome it. Most phase shifters are reciprocal networks, meaning that they work effectively on signals passing in either direction. Phase shifters can be controlled electrically, magnetically or mechanically. All of the phase shifters described below are reciprocal networks; we will concentrate mainly on those that are electrically-controlled.

While the applications of microwave phase shifters are numerous, perhaps the most important application is within an electrically steerable array (ESA), in which the phase of a large number of radiating elements are controlled to force the electro-magnetic wave to add up at a particular angle to the array. The total phase variation of a phase shifter need only be 360 degrees to control an ESA of moderate bandwidth. Networks that stretch phase more than 360 degrees are often called line stretchers, and are constructed similar to the switched line phase shifters to be described below.

Phase shifters can be analog or digital. Analog phase shifters provide a continuously variable phase, perhaps controlled by a voltage. Electrically controlled analog phase shifters can be realized with varactor diodes that change capacitance with voltage, or non-linear dielectrics such as barium strontium titanate, or ferro-electric materials such as yttrium iron garnet. A mechanically-controlled analog phase shifter is really just a mechanically lengthened transmission line, often called a trombone line. Analog phase shifters are a mere side-show and will not be covered here in depth at this time. If you are interested in more information on any of these analog phase shifter topics, let us know and we will try to accommodate you.

Most phase shifters are of the digital variety, as they are more immune to noise on their voltage control lines. Digital phase shifters provide a discrete set of phase states that are controlled by two-state "phase bits." The highest order bit is 180 degrees, the next highest is 90 degrees, then 45 degrees, etc, as 360 degrees is divided into smaller and smaller binary steps. A three bit phase shifter would have a 45 degree least significant bit (LSB), while a six bit phase shifter would have a 5.6 degree least significant bit. Technically the latter case would have a 5.625 degree LSB, but in the microwave world it is best to ignore precision that you cannot obtain. If you can't comprehend this point, you might want to consider a different career such as accounting.

The convention followed for phase shifters is that the shortest phase length is the reference or "off" state, and the longest path or phase length is the "on" state. Thus a 90 degree phase shifter actually provides minus ninety degrees of phase shift in its

"on" state.

Switched-line phase shifter

A simple switched-line phase shifter is shown in Figure 1. The phase shift can easily be computed from the difference in the electrical lengths of the reference arm and the delay arm. The SPDT switches can be realized in a wide variety of ways, using FET, diode, or MEM (micro-electro-mechanical) switches. Typically the combined isolation of the two switches must exceed 20 dB in the design frequency band, or there will be ripple in the amplitude and phase response due to leakage of the "off" arm.
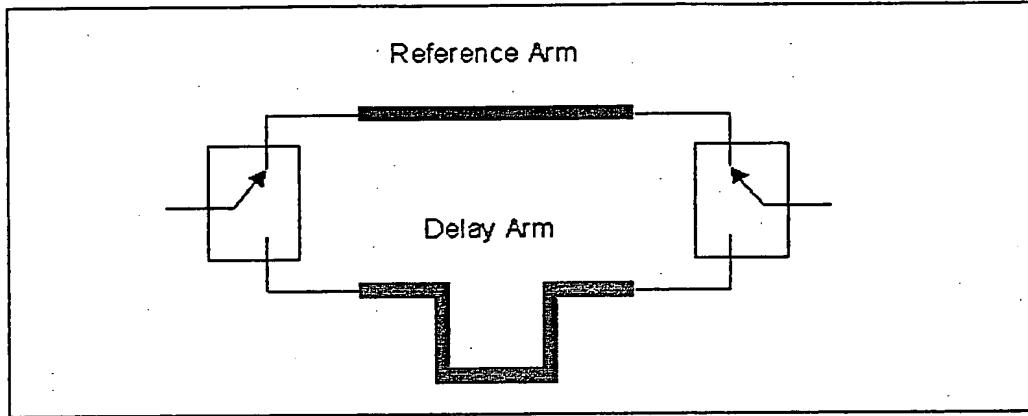
Figure 1. Switched line phase shifter topology

It is important to choose a switch technology appropriately for the frequency band of interest. PIN diode switches are often used through 18 GHz for "chip-and wire" construction (this practice is known as MIC, or microwave integrated circuit). In MMIC design (monolithic microwave integrated circuit), the switches are often realized with FETs, presently at frequencies up to 94 GHz. The weird thing here is that a diode is usually a better switch element than a FET, but when employed on a monolithic circuit, FETs can overcome their off-state capacitance by using a shunt inductor trick at very high frequencies (we will cover that topic at a future time in a section about microwave switches... UE). Diodes are almost never employed monolithically (exceptions are offered by Alpha, TriQuint and M/A-COM), so they have to suffer the variations in wirebond inductance associated with MIC construction, and hence the frequency limitation. An example of a millimeter-wave MMIC switched-line phase shifter is shown in Figure 2. The insertion loss of a switched-line phase shifter is dominated by the switch losses. Typical values are one dB loss per bit through X-band, 2 dB per bit at Ka band and 3 dB or more per bit at W-band. Two control signals are always required for switched line phase shifters.

Figure 2. Example of 6-bit MMIC switched-line phase shifter
(courtesy of the crummy web page we stole this photo from!)

Figure 3 shows the response of an ideal switched-line phase shifter. The difference in length between the reference arm and the delay arm is one-quarter wavelength at 10 GHz. Such a design would be used to provide a 90-degree phase shift at 10 GHz as shown (see the green trace on the plot). Switched-line phase shifters are often used for the two largest phase bits of a multi-bit phase shifter (180 and 90 degrees). Less complex circuits such as loaded-line elements can be used for 45 degree and lesser bits (see the loaded-line phase shifter discussion below).
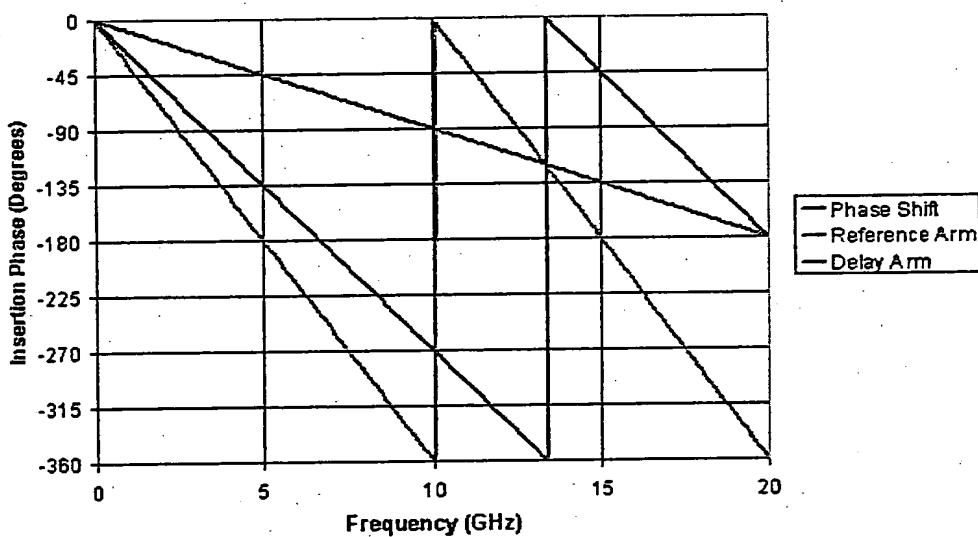
Figure 3. Ideal switched-line phase shifter response, 10 GHz 90 degree bit

High-pass/low-pass phase shifter

If a constant phase shift is desired over a wide frequency range, the switched line phase shifter isn't going to cut it. A high-pass/low-pass phase shifter can provide near constant phase shift over an octave or more. By "high-pass/low-pass" we refer to the fact that one arm forms a high-pass filter while the opposite arm forms a low-pass filter. A second advantage of the high-pass/low-pass phase shifter is that it offers a very compact layout because lumped elements are typically used instead of delay lines. This is an important consideration for "low frequency" designs (i.e. below X-band) because delay transmission lines can be quite large. The cut-off frequencies of the two filter networks obviously must be outside of the phase shift band for this scheme to work. Figure 5 shows a predicted phase response for a high-pass/low-pass 90-degree phase shifter optimized for C-band operation. The values of the lumped elements in this simulation are $C1=1.40$ pF, $L1=2.09$ nH, $C2=0.40$ pF, and $L2=0.63$ nH (referring to Figure 4). Switch insertion phase contributions were neglected in this

simulation. Note that between 4 and 8 GHz the phase shift (green trace) stays within -90 to -99 degrees, a nearly flat response that is not possible from a switched line phase shifter. High-pass/low-pass phase shifters usually require two control signals. By our Microwaves101 convention, the low-pass arm provides the reference state, as it provides the least-negative insertion phase.

Guess what? In practice, the distinction between switched-line and high-pass/low-pass phase shifters is blurred. Lumped capacitors are employed in the filter networks, but the inductors are really just transmission lines of high characteristic impedance.
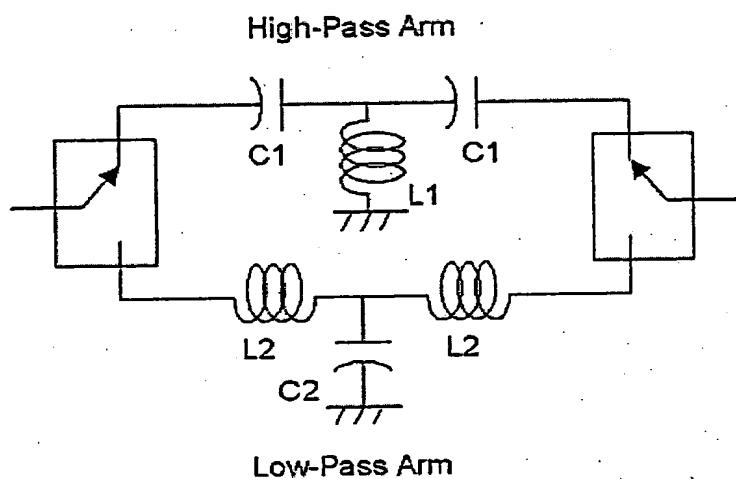
Figure 4. High-pass/low-pass phase shifter topology
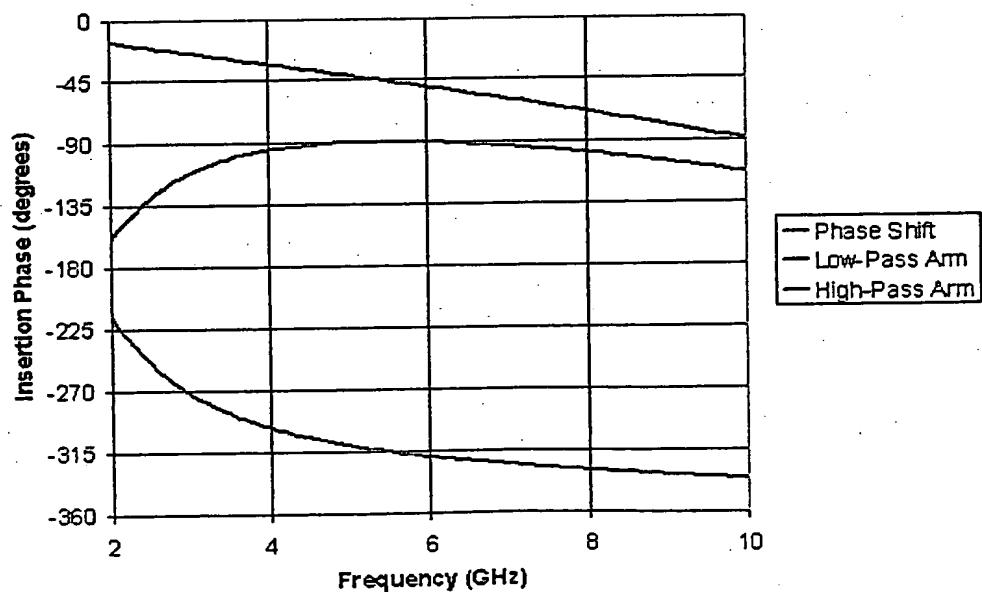
Figure 5. High-pass/low-pass phase shifter, C-band 90 degree bit

Loaded-line phase shifter

Another category of phase shifter is the loaded-line phase shifter, which is often used for 45 degree or lower phase shift bits. An example of a loaded-line phase shifter is shown in Figure 6. The loads ZL are synthesized such that they create a perturbation in the phase of the signal when switched into the circuit, while they have only a small effect on the amplitude of the signal. The loads must have a very high reflection coefficient in order to minimize the loss of the phase shifter (they should utilize purely reactive elements). Obviously the loads ZL must not be too close to a short circuit in phase angle, or the phase shifter will suffer extreme loss. By spacing the reactive loads approximately a quarter-wave apart, the amplitude perturbation can be minimized and equalized in both states. The phase versus frequency response of a loaded line phase shifter is usually flatter than the switched line phase shifter, but not usually as flat as the high-pass/low-pass phase shifter. Usually only one control signal is required for a loaded-line phase shifter, since the loads can be biased simultaneously.
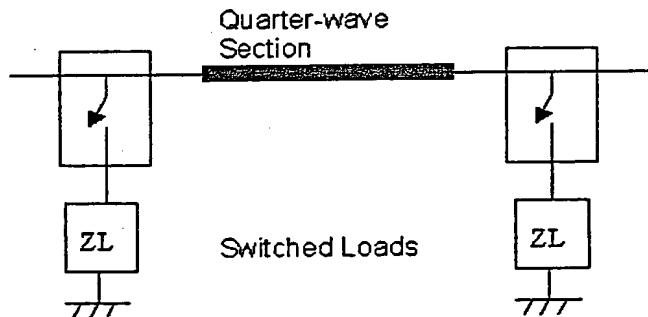
Figure 6. Loaded-line phase shifter

Quadrature phase shifter

A close relative to the loaded-line phase shifter that we will refer to as the "quadrature phase shifter" is shown in Figure 7. Here a quadrature coupler splits the input signal into two signals 90 degrees out of phase (the definition of "quadrature" is two signals 90 degrees apart, click here for more info on quad couplers). These signals reflect from a pair of switched loads, and combine in phase at the phase shifter output, as long as the loads are identical in reflection coefficient (both magnitude and phase). Unlike the loaded line structure discussed previously, the quadrature phase shifter can be used to provide any desired phase shift. Ideally, the loads should present purely reactive impedances, which can range from a short circuit to an open circuit or anything in between. This structure provides a bandwidth of up to an octave, depending on the bandwidth of the quadrature coupler itself. The coupler can be a

Lange or a box hybrid on microstrip, or an overlay coupler in a stripline circuit. The size of a quadrature phase shifter is directly related to the frequency band of operation, as the coupler typically uses one or more quarter-wave sections. Only one control signal is required for a quadrature phase shifter, since the loads can be biased simultaneously.

Quadrature Coupler

Switched Loads

ZL   ZL
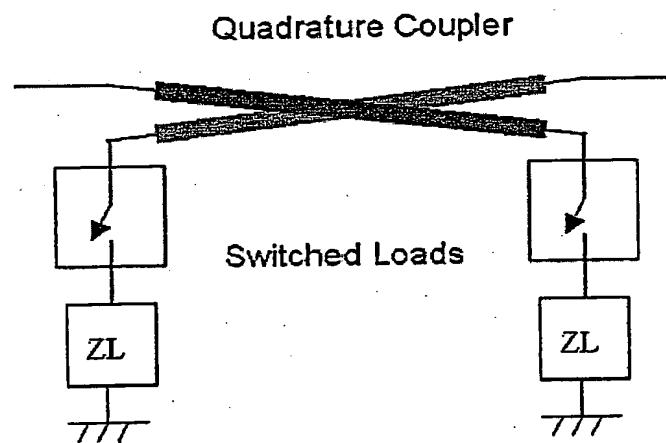
Figure 7. Quadrature phase shifter

Rat-race phase shifter

A clever topology for a 180 degree phase bit is shown in Figure 8. Here a rat-race 180 degree coupler is used with a pair of switched loads. for more info on rat-race couplers, click here. In order for this scheme to work, the switched loads have to present high reflection coefficients and must remain 180 degrees out of phase in both states. For example, an "anti-parallel" pair of diodes can be used as loads, where one is biased on while the other is biased off. As the signal enters from the left it splits 180 degrees out of phase to the loads ZL and -ZL. The signal pair reflects off the loads in phase, and combines at port 3. In practice the parasitics of the switched diode loads (the off-state capacitance of the diodes) tend to cancel from each other, and a beautiful 180 degree phase shifter results (this is not the case in a quadrature phase shifter). The predicted response of a 35 GHz rat-race phase shifter design using 20 femto-Farad, 4.5 ohm diodes is shown in Figure 9. Note that from 25 to 45 GHz the phase error is less than +/-15 degrees. The size of a rat-race phase shifter is directly related to the frequency band of operation, as the circumference of the rat-race coupler is 1.5 wavelengths at the center frequency. If this topology looks familiar, it is because it is similar to a well-known mixer circuit. Two control signals are required for the rat-race phase shifter, as the loads must be kept in opposite states.

Ratrace Coupler
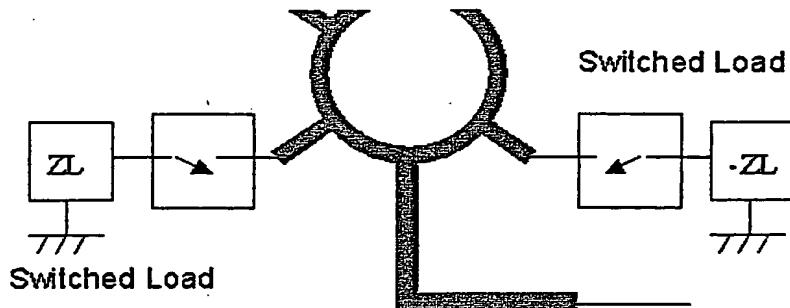
Figure 8. Rat-race phase shifter (180 degree bit)
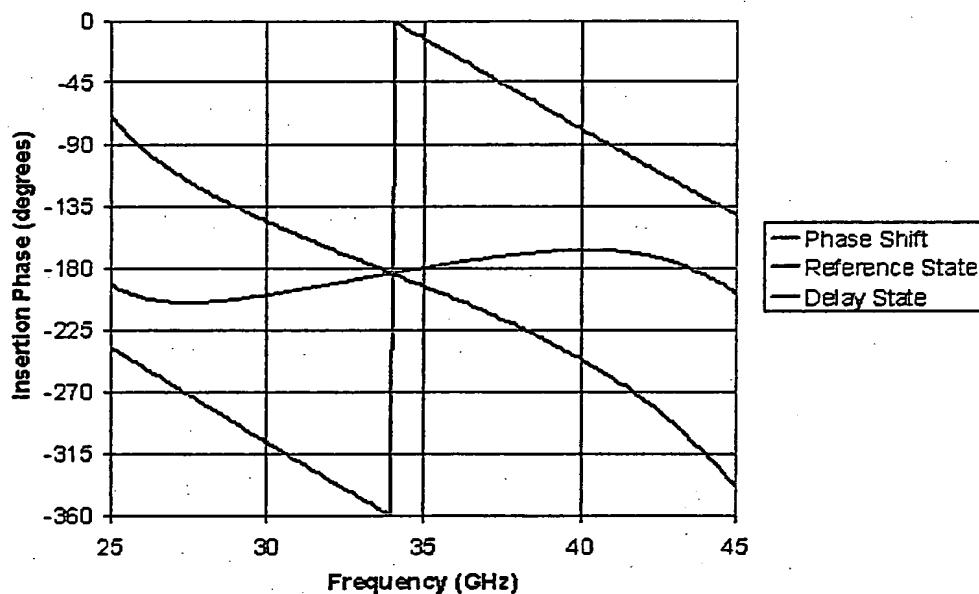
Figure 9. Predicted response of Ka-band rat-race phase shifter

If you know of any phase shifter topologies not covered that should be described here, drop us a line and we will add your knowledge to this chapter! Want to donate a photo of a phase shifter you designed? Send it our way and we might get your 15 minutes of fame if we decide to put it on this page...

- UE

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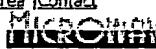
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